

# Highly Ionized Absorption in the X-ray Spectrum of Cyg X-1

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Using the Chandra High Energy Transmission Grating Spectrometer (HETGS), we have found significant absorption features in the X-ray spectrum of Cyg X-1 taken in the continuous clocking mode. These features include resonance lines of He-like ions of S, Si, and Mg; the Ly alpha lines of H-like S, Si, Mg, and Ne; and several lower ionization lines of Fe XX, XXII, and XXIV. Preliminary analysis shows that the lines are resolved in many cases, giving line widths of order 300 km/s and are redshifted by  $460 \pm 10$  km/s. These features are interpreted in the context of an accreting stellar wind model that is ionized by the X-ray source. In addition, there are clear absorption features due to neutral Mg, Fe, and O in the interstellar medium.

## 1. Introduction

Cyg X-1 has been observed several times with the High Energy Transmission Grating Spectrometer (HETGS) on the *Chandra* X-ray Observatory. The first observation [5] shows details of the structures of the ionization edges from neutral species in the interstellar medium. In particular, the O K and Fe L edges showed significant structure that had been unobservable at low spectral resolution. The Ne K edge was unresolved but the nearby continuum showed subtle features that could be attributed to Fe XX. There were other weak, unresolved features in the spectrum that supported in the interpretation that we are observing Cyg X-1 through a low density ionized gas that is associated with Cyg X-1.

A second observation with the HETGS that was taken at a different orbital phase and in a different instrument mode. We find many redshifted absorption features from highly ionized species of S, Si, Mg, Ne, and Fe. We present a preliminary analysis of this observation.

## 2. Chandra HETGS Spectra

Cyg X-1 was observed on 12 January 2000 (MJD = JD - 2400000.5 = 51555.34 - 5.51). The orbital phase for this observation was 0.84, based on a recent orbital ephemeris [1]. For the first observation [5], the orbital phase was 0.93, while in a third observation, the orbital phase was 0.76, nearly perpendicular to the line between the compact and companion stars [4]. The total exposure time was 12677.5 s. The Advanced CCD Imag-

ing Spectrometer (ACIS-S) detector was used for readout and was operated in the so-called “continuous clocking” (CC) mode. This mode is described in detail in the *Chandra* Proposer’s Observatory Guide (p. 101). Briefly, in this mode, the charge is shifted row by row to the frame storage buffer at 2.84996 ms intervals. Imaging information along the readout direction is lost in favor of improved event timing.

The *Chandra* HETGS spectrum of Cyg X-1 is shown in Figs. 1 and 2. A fit to a simple power law in the 2-10 keV band gives a photon index of 1.73. The residuals (Fig. 1) show that there is a soft excess that is usually attributed to a disk blackbody. In the first HETGS observation,  $kT$  of the disk was about 200 eV [5]. In addition to absorption edges from neutral gas in the interstellar medium, there are many narrow absorption lines. The depths of the Ne K and Fe L absorption edges are consistent with the edge strengths obtained from the first observation where  $N_H$  was estimated to be  $6.2 \times 10^{21} \text{ cm}^{-2}$  [5].

In order to show the absorption lines more clearly, the HETGS medium energy grating (MEG) and the high energy grating (HEG) spectra were combined at a binning of 0.01 Å (Fig. 2). There are more than a dozen narrow absorption lines of highly ionized species, ranging from Fe XVII to S XVI. The lines are redshifted by 300 to 800 km/s but are generally consistent with the weighted mean:  $460 \pm 10$  km/s (see Fig. 3). The lines are resolved in HEG spectra (and often in the lower resolution MEG spectra as well), giving Doppler line widths of order  $300 \text{ km s}^{-1}$  (FWHM). In some cases, blends cause the lines

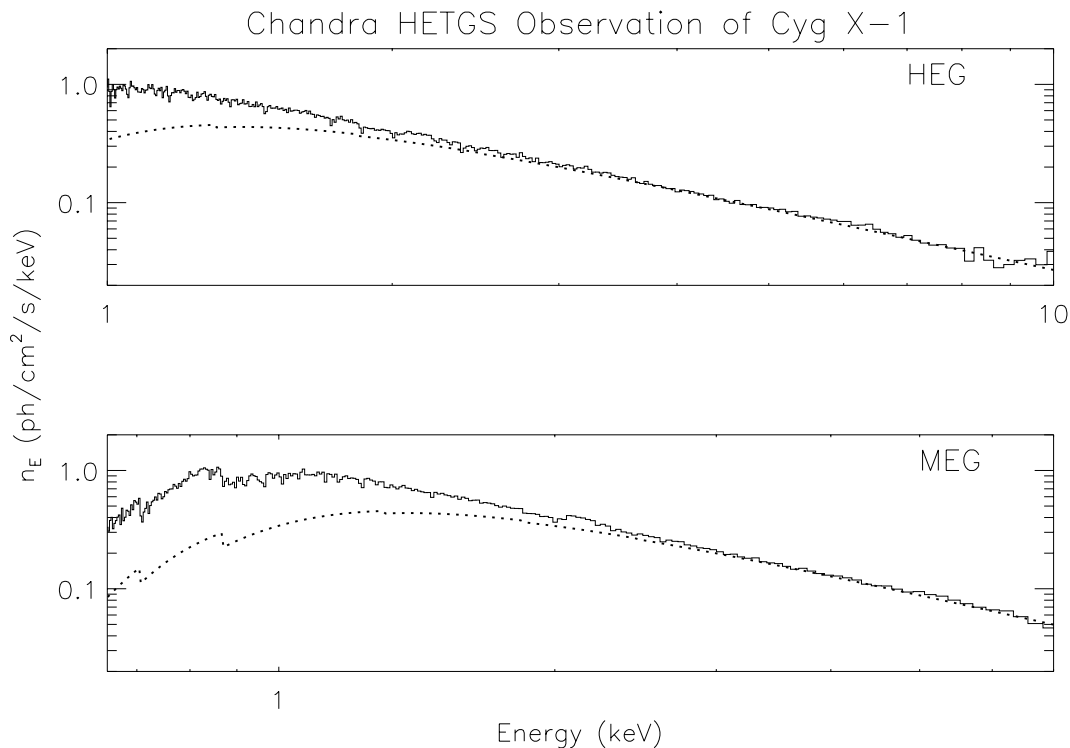


Figure 1. 1-10 keV spectrum of Cyg X-1 from the *Chandra* HETGS. Spectra from the HEG (top) and MEG (bottom) portions of the HETGS are shown separately. The data have been heavily binned to show the continuum shape. The model (dotted line) is a simple power law with  $\Gamma = 1.73$  absorbed by a neutral column density of  $N_H = 6 \times 10^{21} \text{ cm}^{-2}$  [5]. A soft excess is attributed to a thermal component is detected below 2 keV. Narrow absorption features are observed in the 1.5-2.5 keV range. These are more clearly shown in Fig. 2.

to be broader than expected.

Practically no Ly  $\beta$  lines are detected while Ly  $\alpha$  lines are strong, so we infer that the lines are not saturated and that the absorbing gas probably covers more than  $\sim 50\%$  of the source. Assuming complete coverage, we estimated column densities from fits of Gaussian models jointly to the original MEG and HEG data. The results are shown in Fig. 3. The column densities are between  $10^{16} \text{ cm}^{-2}$  and  $10^{17} \text{ cm}^{-2}$ , which, using solar abundances, correspond to equivalent hydrogen column densities of the order of  $10^{20-21} \text{ cm}^{-2}$ . There is trend that the column densities of He-like ions are systematically lower than the corresponding H-like ions, which could indicate that the photoionized plasma has a high temperature or the emission from these ions originate

from different emission zones. We note that the result for all the Fe XVII transitions are consistent with each other.

### 3. Discussion

We consider a simple working hypothesis in which the narrow lines result from absorption by ionized gas as it is transferred from the companion star to the black hole. The companion is a supergiant O star with a radiatively driven wind with a maximum velocity of  $\sim 1500 \text{ km s}^{-1}$  [2]. Cyg X-1 gravitationally focusses and accretes this wind from the companion [3] although the companion may be very close to filling its Roche lobe [7]. The wind from the companion is expected to be too cool ( $T \sim 10^5 \text{ K}$ , as in Vela X-1

[6]) to ionize S and Si to the H- and He-like states, so the ionization mechanism is most likely photoionization by the hard X-ray continuum. This continuum is thought to result from Comptonization of the accretion disk's thermal radiation in an extremely hot corona, so the absorbing gas must have a much larger physical scale.

In general, the wide range of observed ionization states (Fe XVII to S XVI) would not be found in gas of a single ionization parameter,  $\xi \equiv L_x/(nr^2)$ , so  $nr^2$  probably varies significantly along the line of sight. Lines of these strengths were not observed in the first observation, so the conditions under which they are detected may depend on the luminosity state of the illuminating X-ray source or the orbital phase. The source was  $\times 2$  brighter during the first observation so it may be that the higher X-ray luminosity completely ionized the accreting material. On the other hand, the orbital phase was 0.93, so the wind may have been mostly obscured by the companion star.

Remarkably, we do not observe a wide spread of line velocities (Fig. 3), but a quite narrow ( $\pm 150$  km s $^{-1}$ ) distribution around 450 km s $^{-1}$ . At the closest approach to the surface of the companion, about one stellar radius, the line of sight to Cyg X-1 will encounter a wind velocity of order 650 km s $^{-1}$ . In the focussed wind model, the velocity vector is not directed strictly radially, so we observe gas that appears to be on an accretion trajectory. Using solar abundances, the column density of the absorbing material is of order  $10^{20-21}$  cm $^{-2}$ , which is well below the value of  $10^{23}$  cm $^{-2}$  inferred from *RXTE* ASM observations [7]. This could indicate that we observe either a physically narrow plasma flow (a “streamer” or “ribbon”) or only a smaller, more distant region in the plasma flow that is either shadowed from the ionizing source or that is only partially ionized.

## REFERENCES

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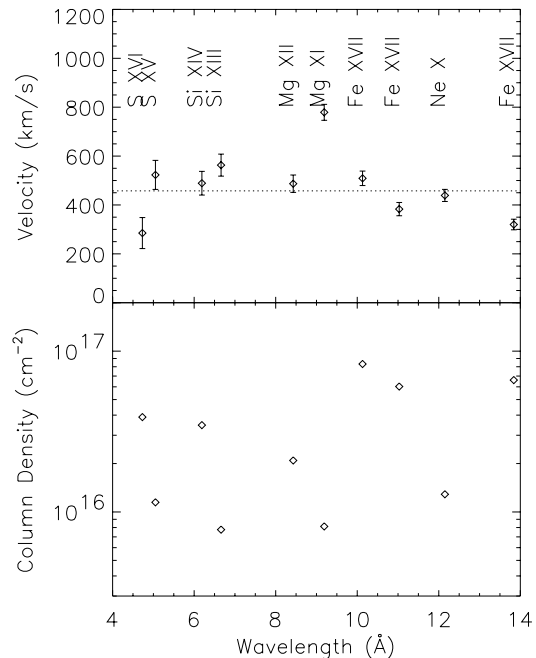


Figure 3. The velocities and column densities of lines detected in the Cyg X-1 X-ray spectrum as a function of their observed wavelengths. The dotted line in the top panel gives the average redshift of 460 km/s, excluding Mg XI.

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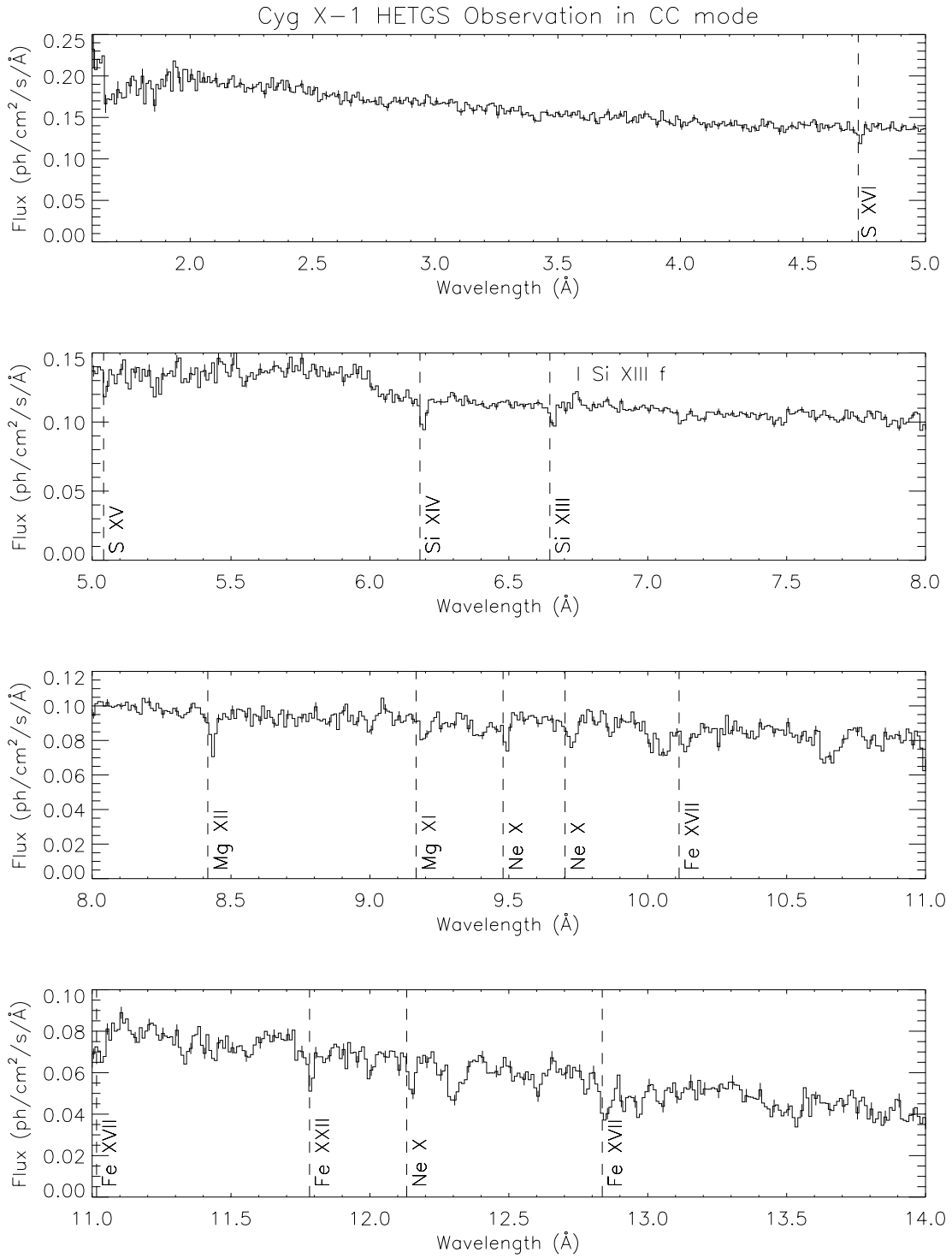
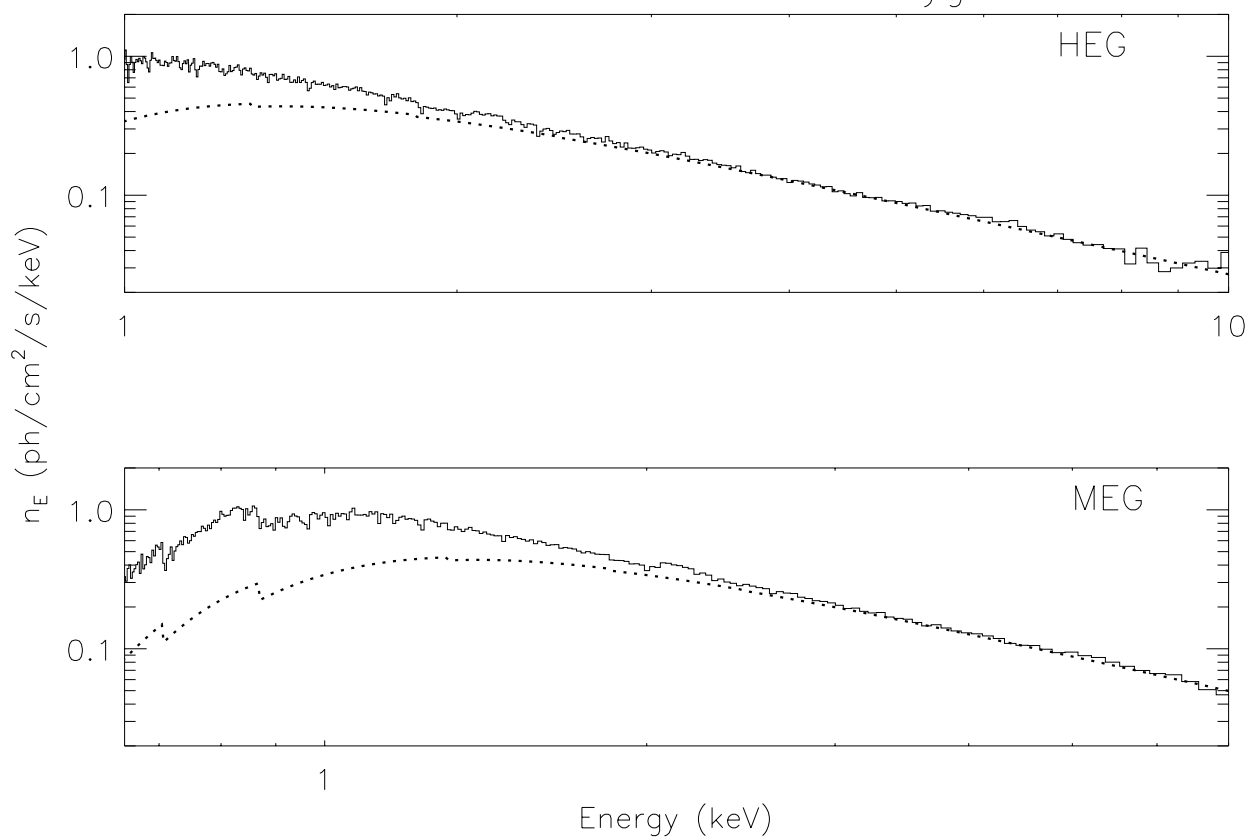


Figure 2. *Chandra* HETGS spectrum of Cyg X-1. The MEG and HEG spectra were combined at a binning of 0.01 Å. Note the many absorption lines of highly ionized species, ranging from Fe XVII to S XVI. The vertical dashed lines mark the rest wavelengths of each line. The average redshift is  $460 \pm 10$  km/s.

# Chandra HETGS Observation of Cyg X-1



Cyg X-1 HETGS Observation in CC mode

